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Full-3D Surveying of Caves: A Case Study of Märchenhöhle (Austria)

Andreas RONCAT¹, Yuri DUBLYANSKY², Christoph SPÖTL², Peter DORNINGER¹

¹ Institute of Photogrammetry and Remote Sensing, Vienna University of Technology, Austria, ar@ipf.tuwien.ac.at, pdo@ipf.tuwien.ac.at
² Institute of Geology and Paleontology, Leopold Franzens Universität Innsbruck, Austria, juri.dublyanski@uibk.ac.at, christoph.spoetl@uibk.ac.at

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Abstract

This study presents the potential of terrestrial laser scanning for full-3D mapping of caves. The technique of laser scanning has become standard for medium and large-scale surveying of topographic surfaces, but has so far only seldom been used in karst studies. On the example of the hypogene cave Märchenhöhle (Austria, cadastre #1742/17) we describe both the theoretical background and the actual work flow from the data capture to the derivation of a digital 3D model of a cave. The model ensures rigorous documentation and offers possibility to complement field observations on cave morphology with subsequent, more-detailed, examination in the office. This makes morphogenetic interpretations more thorough and objective than was possible with conventional cave maps.
1 Introduction

Mapping of caves is usually done using instruments such as (electronic) distance meters, compasses and tilt meters. Although computer support is available for data acquisition, processing and creating cave maps, there is still a lot of manual work associated with this task (cf. Plan and Xaver 2010). As a result, the quality of the final map heavily depends on the experience and the cartographic skills of individual surveyors.

In speleogenetic studies (that is, studies aimed at deciphering origin of caves and details of specific processes which led to cave formation) besides gross cave morphology, meso- and micro-morphological features are of great importance (Dublyansky 2012). These smaller-scale features are typically not represented on the standard cave maps. For specialized morphogenetic maps, such small-scale features must be documented and interpreted on-site, and then represented on the final maps qualitatively (mostly, as symbols).

Usage of image-based photogrammetric surveying is limited in cave studies primarily because of the difficulty of achieving homogeneous light conditions.

Laser scanning is independent of light conditions and delivers high resolution 3D point clouds as input for both mapping and quantitative analysis of small-scale features. Its principles and usage in the different scientific fields are presented in Section 2. We further discuss application of the laser scanning technique to mapping of Märchenhöhle (Fairy tale cave), a hypogene cave in Styria, Austria, in Section 3. The laser scanner data recorded in this cave by the authors in a field campaign in July 2010 are presented in Section 4. The subsequent section deals with the derived results, including full-3D models of Märchenhöhle’s main chambers. The article concludes with discussion and outlook in Section 6.

2 Laser Scanning

Laser Scanning is an active 3D measurement technique recording 3D point clouds in regular angular patterns. Instruments are available for both the airborne (known as airborne laser scanning, ALS) and the ground-based applications (terrestrial laser scanning, TLS). ALS has become standard for high-resolution topographic data acquisition during the last 15 years (Gomes-Pereira and Janssen 1999; Pfeifer and Mandlburger 2008). For limited areas, TLS has proven to be comparably accurate and efficient for this task, too (Roncat et al. 2010). Besides the use in topographic mapping, ALS is also in widespread use in other scientific fields, such as forestry (Naesset 1997; Hollaus et al. 2007), 3D city modeling (Dorninger and Pfeifer 2008), monitoring of infrastructure (Melzer 2007) and hydrology (Mandlburger et al. 2009), just to name a few. In turn, TLS is widely applied for e.g. monitoring tunnels during the construction phase (Fekete et al. 2010; van Gosliga et al. 2006), cultural heritage documentation (Dorninger and Briese 2005) and inspection of industrial and technical facilities (Kopáčik and Wunderlich 2004).

A recent issue of Zeitschrift für Geomorphology summarizes geomorphological applications of (both terrestrial and airborne) laser scanning (Pfeifer et al. 2011), ranging from glacier surface classification and mass balance analysis to studies of fluvial geomorphology. So far, only a limited number of case studies reports application of laser scanning to mapping caves. One recent example is the survey of the Cueva de los Cristales near Naica, Mexico (Canavese et al. 2009).

Figure 1 depicts the scanning geometry and the resulting point cloud of a TLS scan (Kraus 2007).
The TLS scanners may employ three operating principles (Beraldin et al. 2010):

- **Time-of-flight measurement**: A short laser pulse is transmitted and the arrival time of its echo is recorded. Multiplication with the speed of light leads to the range of the reflecting surface. This kind of scanners normally operates in ranges from several meters up to some hundred meters.

- **Phase measurement**: These scanners emit a modulated laser signal, using either continuous wave (CW), amplitude modulation (AM) or frequency modulation (FM). Correlation of the return signal with a copy of the emitted signal generated in the instrument leads to the range of the reflecting surface. Phase ambiguity limits the maximum recordable distance to normally approx. $80 - 100$ m.

- **Triangulation-based measurement**: The projection of the laser ray on the target surface is captured by a scanner-internal camera. Since the relative position and attitude of the laser ray and the camera are known, this allows for the calculation of the three-dimensional coordinates of the projected point by spatial intersection. These scanners operate at distances from some decimeters up to some meters.

The instrument used in this study was a phase-measurement scanner (see Section 4).

3 **The Study Site – Märchenhöhle**

Märchenhöhle (cadastre # 1742/17) is located at the southern margin of the Northern Calcareous Alps, near Eisenerz (Styria, Austria; see Figure 2 (Wikimedia 2011; BEV 2011)). This 135 m-long cave occurs near the crest of a limestone ridge at approx. 1500 m a.s.l., some 900 m above the valley floor. The cave consists of several near-isometric chambers separated by relatively narrow openings. The lower parts of cave walls are coated with a mammillary calcite crust (cave clouds; see Figure 3). Above this crust the internal surface of the cave exhibits a wealth of peculiar smaller-scale corrosional features (e.g., funnel-shaped chambers with flat roofs, cupolas, cup-shaped pockets on inclined walls, etc.).
4 Data Sets

The scanning campaign took place on July 22, 2010 using a z+f Imager 5006i terrestrial laser scanner operating according to the phase-measurement principle (Zoller+Fröhlich 2011). This instrument is capable of recording max. 800 million points per scan (40,000 lines x 20,000 points per line, scan mode “Ultra High”) within a scan time of 27 minutes. The maximal range to be recorded is approx. 80 m. The maximum resolution results in a point spacing of 1.6 mm at 10 m distance. Table 1 gives the details to the single scans recorded in the scanning campaign.
Table 1: Overview of the 11 recorded scans.

<table>
<thead>
<tr>
<th>Scan ID</th>
<th>Scan Mode</th>
<th>Number of recorded points</th>
<th>Acquisition time</th>
<th>Local Pos. [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Super High</td>
<td>200,000,000</td>
<td>6 min 44 sec</td>
<td>(0.000, 0.000, 0.000)</td>
</tr>
<tr>
<td>2</td>
<td>Super High</td>
<td>200,000,000</td>
<td>6 min 44 sec</td>
<td>(8.691, 2.736,-1.300)</td>
</tr>
<tr>
<td>3</td>
<td>Super High</td>
<td>200,000,000</td>
<td>6 min 44 sec</td>
<td>(9.920, 8.126,-1.755)</td>
</tr>
<tr>
<td>4</td>
<td>Super High</td>
<td>200,000,000</td>
<td>6 min 44 sec</td>
<td>(13.775, 8.973,-0.503)</td>
</tr>
<tr>
<td>5</td>
<td>Super High</td>
<td>200,000,000</td>
<td>6 min 44 sec</td>
<td>(12.310,14.367,-2.399)</td>
</tr>
<tr>
<td>6</td>
<td>High</td>
<td>50,000,000</td>
<td>3 min 22 sec</td>
<td>(4.523,12.389,-0.710)</td>
</tr>
<tr>
<td>7</td>
<td>High</td>
<td>50,000,000</td>
<td>3 min 22 sec</td>
<td>(2.061, 12.059, 0.809)</td>
</tr>
<tr>
<td>8</td>
<td>High</td>
<td>50,000,000</td>
<td>3 min 22 sec</td>
<td>(9.522, 13.447,-1.438)</td>
</tr>
<tr>
<td>9</td>
<td>Super High</td>
<td>200,000,000</td>
<td>6 min 44 sec</td>
<td>(4.973, 21.830,-1.697)</td>
</tr>
<tr>
<td>10</td>
<td>High</td>
<td>50,000,000</td>
<td>3 min 22 sec</td>
<td>(16.678, 15.971,-2.834)</td>
</tr>
<tr>
<td>11</td>
<td>Super High</td>
<td>200,000,000</td>
<td>6 min 44 sec</td>
<td>(18.682, 20.461,-1.898)</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td>1,600,000,000</td>
<td>1h 00 min 36 sec</td>
<td></td>
</tr>
</tbody>
</table>

Since the data were acquired from different positions, accurate determination of the relative positions and attitudes of the individual point clouds was necessary. This is known as “relative orientation” in photogrammetry and geodesy (Kraus 2007) and as “co-registration” in the field of computer vision (Shapiro and Stockman 2001). In our case, the relative orientation was established in a two-step approach: the coarse relative orientation was determined using coded targets (as visible in Figure 4) using the software delivered by the scanner’s manufacturer. It was refined using an ICP (iterative closest point (Besl and McKay 1992)) algorithm implemented in the Geomagic Studio software (Geomagic 2011). The first step uses some distinct points in two scans with known point-to-point correspondence whereas the latter makes use of the whole point clouds. However, ICP needs good initial values for the relative orientation to perform adequately.

It has to be mentioned that our study did not require an absolute georeference (i.e. position and attitude of the overall point cloud w.r.t. a superior coordinate system such as national coordinate systems or WGS84). The local coordinate system was defined by taking the first scan position as the origin, defining the local plumb line (z axis) using the tilt sensor of the scanner and taking the scanner’s horizontal 0° line as the y axis. A cartesian right-handed coordinate system was uniquely determined in this way.
After the relative orientation, the point cloud underwent subsequent processing steps such as filtering, homogenization and correction of systematic errors (cf. Dorninger et al. 2008; Molnár et al. 2009; Nothegger and Dorninger 2007). These steps were necessary to reduce the amount of data without losing significant details to enable the final 3D modeling of the cave (see Section 5) in reasonable processing time.

5 Results

Co-registration resulted in overall 3D point cloud covering the largest part of the cave. A floor plan of this point cloud was compared to a map of the cave produced by “traditional” surveying technique in 1971. Although absolute georeference was not available for both maps, they show a good coincidence (see Figure 5).

As a next step, horizontal profiles were derived from this point cloud. Each profile consists of the points located at a specific height ±5 cm. Colour coding of the single points according to their local height allows for the detection of vertical structures (Figure 6). The profiles are available as GeoTIFF images and can thus be used for digitization in CAD software packages.

The core result of this study was the derivation of a triangulated 3D model of the whole area of interest which is depicted in Figure 7. Whereas the original point cloud consisted of more than $10^9$ points, the resulting 3D model contains approx. 12 million triangles. Although the point cloud was greatly reduced, sophisticated filtering allowed to preserve also small features such as minor fractures and inclined pocketed walls.

Figure 4: Coded targets placed on top of rocks. These targets were used for determining the relative orientation of the scans. Photograph by Harald Auer.
Figure 5: Overlay of a map of Märchenhöhle (black and white) and a floor projection of the recorded point cloud (blue). The two map images were manually adjusted, but show nevertheless good coincidence.

Figure 6: Horizontal profiles of the point clouds in the local heights of −1.40 m (left) and −0.60 m (right). Blue corresponds to the local height minus 5 cm, black to the local height and red to the local height plus 5 cm.
Figure 7: Visualization of the triangulated 3D model of Märchenhöhle. Note complex, compartmentalized gross morphology of the cave.

Figure 8 shows a visualization of the 3D reconstruction of the cave’s central chamber (viewed from outside). One shortcoming of the current results is the missing intensity and colour information. Although intensity information was recorded by the scanner for each 3D point, the intensity values ought to be radiometrically calibrated before further use. Radiometric calibration will be a future step in the processing of the presented data sets. Photographs providing colour information were not taken area-wide because of the light conditions.

6 Discussion and Outlook

A hypogene cave in Austria was used as a test-ground for developing measurement techniques and subsequent data processing schemes for surveying caves in full-3D. The outcomes, be it point-based or based on a 3D triangulation, allows for quantitative analysis of the cave’s general shape and also small-scale features. In addition to the geometric data captured with laser scanning, intensity information has potential of increasing the information content of the derived models.
Figure 8: Visualization of the triangulated 3D model of one of the chambers of Märchenhöhle and explanatory drawings. Note the complex morphology of the chamber and a wealth of the small-scale features recognizable on the model surface.

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